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Quantum-dot cellular automata devices and architectures

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Abstract. We discuss novel nanoelectronic architecture paradigms based on cells composed of coupled quantum-dots. Boolean logic functions may be implemented in specific arrays of cells representing binary information, the so-called Quantum-Dot Cellular Automata (QCA). In addition, we discuss possible realizations of these structures in a variety of semiconductor systems (including GaAs/AlGaAs, Si/SiGe, and Si/SiO₂), rings of metallic tunnel junctions, and candidates for molecular implementations.

1 Introduction

Silicon technology has followed Moore's Law remarkably closely for more than three decades. However, there are indications now that this progress will slow, or even come to a standstill, as technological and fundamental limits are reached [1]. This slow-down of silicon ULSI technology may provide an opportunity for alternative device technologies. Among the chief technological limitations responsible for this expected slow-down of silicon technology are the interconnect problem and power dissipation [2]. However, these obstacles for silicon circuitry may present an opportunity for alternative device technologies which are designed for the nanometer regime and which are interconnected in an appropriate architecture.

In this paper, we describe our ideas of using nanostructures (more specifically, quantum dots) which are arranged in locally-interconnected cellular-automata-like arrays. We will demonstrate that suitably designed structures, the so-called "Quantum-Dot Cellular Automata" (QCA) [3], may be used for computation and signal processing. The fundamental idea for QCA operation is to encode information using the charge configuration in a cell, which is more naturally suited to nanostructures. This is an important break with the transistor paradigm, where binary information is encoded utilizing voltage-controlled current switches.

2 Quantum-dot cellular automata

Based upon the emerging technology of quantum-dot fabrication, the Notre Dame NanoDevices Group has developed the QCA scheme for computing with cells of coupled quantum dots [3], which will be reviewed below. To our knowledge, this is the first concrete proposal to utilize quantum dots for computing. There had been earlier suggestions that device-device coupling might be utilized in a cellular-automata scheme, alas, without an accompanying proposal for a specific implementation [4].

2.1 A quantum-dot cell

The Quantum-Dot Cellular Automata (QCA) scheme is based on cells which contain quantum dots [3], as schematically shown in Fig. 1(a). The quantum dots are shown

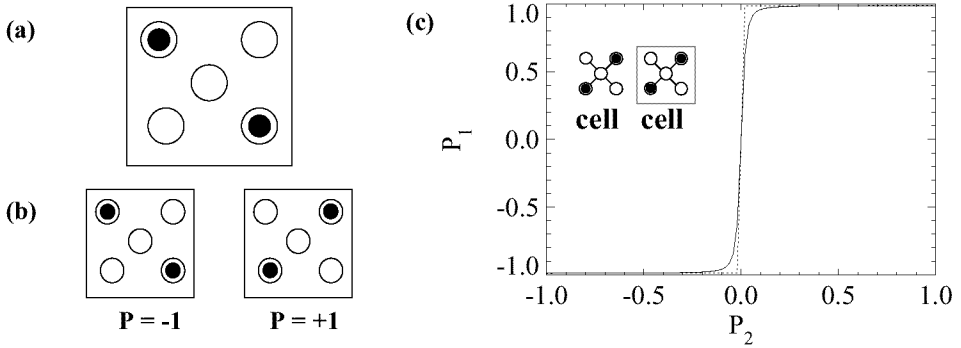


Fig 1. (a) A quantum-dot cell consisting of five dots is occupied by two electrons. (b) The two distinct ground-state configurations with their polarizations. (c) Cell-cell coupling characteristics.

as the open circles which represent the confining electronic potential. In the ideal case, each cell is occupied by two electrons, schematically shown as the solid dots, and each electron is allowed to tunnel between the individual quantum dots in a cell, but not between neighboring cells.

This quantum-dot cell represents an interesting dynamical system. The two electrons experience their mutual Coulombic repulsion, yet they are constrained to occupy the quantum dots. If left alone, they will seek, by tunneling between the dots, the configuration corresponding to the physical ground state of the cell. It is clear that the two electrons will tend to occupy different dots because of the Coulomb energy cost associated with bringing them together in close proximity on the same dot. It is easy to see that the ground state of the system will be an equal superposition of the two basic configurations with electrons at opposite corners, as shown in Fig. 1(b).

2.2 Cell-cell coupling

The properties of an isolated cell were discussed above. The two polarization states of the cell will not be energetically equivalent if other cells are nearby. Here, we study the interactions between two cells, each occupied by two electrons. The electrons are allowed to tunnel between the dots in the same cell, but not between different cells. Coupling between the two cells is provided by the Coulomb interaction between electrons in different cells.

Figure 1(c) shows how one cell is influenced by the state of its neighbor. The inset shows two cells where the polarization of cell 1 (P_1) is determined by the polarization of its neighbor (P_2). Cell polarization P_2 is presumed to be fixed at a given value, corresponding to a certain arrangement of charges in cell 2, and this charge distribution exerts its influence on cell 1, thus determining its polarization P_1 . The important finding here is the strongly non-linear nature of the cell-cell coupling. Cell 1 is almost completely polarized even though cell 2 might only be partially polarized.

2.3 QCA logic

Based upon the bistable behavior of the cell-cell coupling, the cell polarization can be used to encode binary information. We have demonstrated that the physical interactions between cells may be used to realize elementary Boolean logic functions [5]. Figure 2

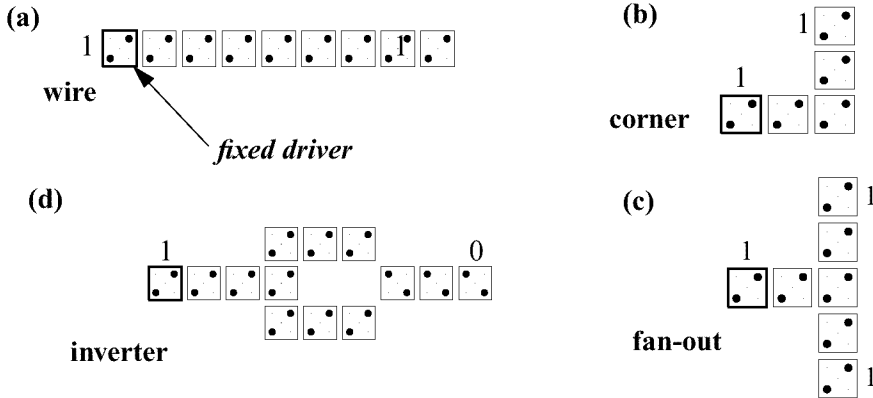


Fig 2. Examples of simple QCA arrays for Boolean logic.

shows examples of simple arrays of cells. In each case, the polarization of the cell at the edge of the array is kept fixed; this is the so-called driver cell and it is plotted with a thick border. We call it the driver since it determines the state of the whole array. Without a polarized driver, the cells in a given array would be unpolarized in the absence of a symmetry-breaking influence that would favor one of the basis states over the other. Each figure shows the cell polarizations corresponding to the physical ground state configuration of the whole array. Fig. 2(a) shows that a line of cells allows the propagation of information, thus realizing a binary wire. Note that only information but no electric current flows down the line, which results in low power dissipation. Information can also flow around corners, as shown in Fig. 2(b), and fan-out is possible, shown in Fig. 2(c). Cells which are positioned diagonally from each other tend to anti-align. This feature is employed to construct an inverter as shown in Fig. 2(d). In each case, electronic motion is confined to within a given cell, but not between different cells. Only information, and not charge, is allowed to propagate over the whole array.

These quantum-dot cells are an example of quantum-functional devices. Utilizing quantum-mechanical effects for device operation may give rise to new functionality. Figure 3 shows the fundamental QCA logical device, a three-input majority gate, from which more complex circuits can be built. The central cell, labeled the device cell, has three fixed inputs, labeled A, B, and C. The device cell has its lowest energy state if it assumes the polarization of the majority of the three input cells. The difference between input and outputs cells in this device, and in QCA arrays in general, is simply that inputs are fixed and outputs are free to change. The inputs to a particular device can come from previous calculations or be directly fed in from array edges. Using conventional circuitry, the design of a majority logic gate would be significantly more complicated, being composed of some 26 MOS transistors. It is possible to “reduce” a majority logic gate by fixing one of its three inputs in the 1 or 0 state. In this way, a reduced majority logic gate can also serve as a programmable AND/OR gate. The new physics of quantum mechanics gives rise to new functionality, which allows a rather

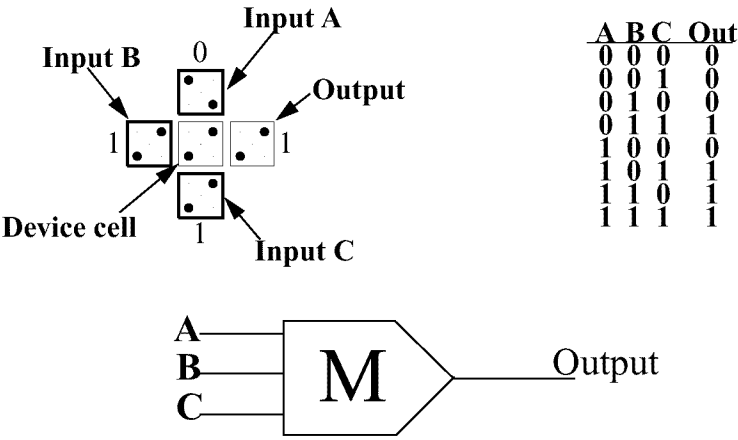


Fig 3. QCA Majority Logic gate with its truth table and logic symbol.

compact realization of majority logic.

2.4 Quantum-dot cellular nonlinear networks

In addition to employing QCA cells to encode binary information, these cells may also be used in an analog mode. Each cell interacts with its neighbors within a certain range, thus forming what we call a Quantum-Dot Cellular Nonlinear Network (Q-CNN) [6]. This way of viewing coupled cells as a nonlinear dynamical system is similar to Cellular Nonlinear (or, Neural) Networks (CNN), which are locally-interconnected structures implemented using conventional circuitry [7]. Each cell is described by appropriate state variables, and the dynamics of the whole array is given by the dynamical law for each cell, which includes the influence exerted by the neighbors on any given cell.

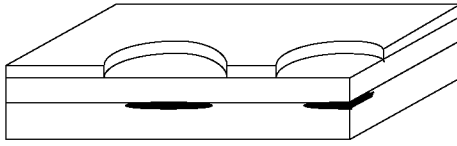
3 Possible quantum-dot cell implementations

3.1 Gate-controlled quantum dots

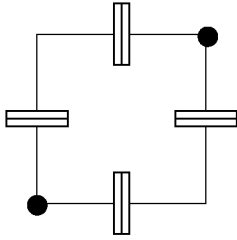
The fabrication of a QCA cell by split-gate technology is a challenging problem, yet appears to be within reach of current lithographic capability [8]. Figure 4 shows a possible physical realization which is based on electrostatic confinement provided by a top metallic electrode. The key implementation challenges are (i) to gain sufficient gate control in order to define quantum dots in the few-electron regime, and (ii) to place these dots sufficiently close to each other in order to make coupling possible [9]. Using these techniques, it is conceivable that coupled-dot cells may be realized in a variety of materials systems, such as III-V compound semiconductors, Si/SiGe heterolayers, and Si/SiO₂ structures.

3.2 Rings of metallic tunnel junctions

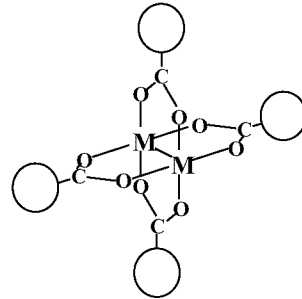
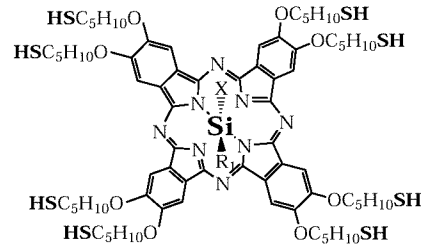
Single-electron tunneling phenomena may also be observed in metallic tunnel junctions, also schematically shown in Fig. 4. The tunnel junctions are represented by the capacitor symbols, indicating that they are characterized by their capacitance and tunnel resistance.



Semiconductor Heterostructures



Rings of Metallic Tunnel Junctions



Molecular Structures

Fig 4. Possible QCA implementations using gate-confined quantum dots, rings of metallic tunnel junctions, and molecular structures.

The metallic droplets themselves are the “wires” between the tunnel junctions. Consider now that two extra electrons are added to such a cell, as schematically shown. This cell exhibits precisely the same two distinct ground state configurations as the semiconductor cell discussed above [94]. In addition, the cell-cell coupling, which is purely capacitive, also shows the same strongly non-linear saturating characteristic. The metallic tunnel-junction cell may be used as a building block for more complicated structures, in a fashion completely analogous to the semiconductor implementations. QCA behavior in such structures has been demonstrated in recent experiments [11].

3.3 Possible molecular implementation

QCA room temperature operation would require molecular-scale implementations of the basic cell. In previous work by Fehner and co-workers, a candidate for such a prototypical molecular cell has been synthesized and crystallographically characterized [12]. As schematically illustrated in Fig. 4 (bottom diagram), these molecular substances with the formula $M_2\{[(CO)_9Co_3CCO_2]_4\}$, where $M = Mo, Mn, Fe, Co, Cu$, consist of square arrays of transition metal clusters, each containing three cobalt atoms. Another candidate for QCA implementation are phthalocyanine molecules, also illustrated in Fig. 4 (top diagram), which have recently been synthesized and characterized [13].

4 Conclusion

We have developed a novel nanoelectronic scheme for computing with coupled quantum dots, where information is encoded by the arrangement of single electrons. We have shown that such structures, the so-called Quantum-Dot Cellular Automata, may be used

for binary information processing. In addition, an analog version is also possible, the so-called Quantum-Dot Cellular Nonlinear Networks, which exhibit wave phenomena. We have discussed possible realizations of these structures in a variety of semiconductor systems (including GaAs/AlGaAs, Si/SiGe, and Si/SiO₂), rings of metallic tunnel junctions, and candidates for molecular implementations.

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